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(54) Rendering a color image for an output medium from symbolic image data.

(57) A method of rendering a colour image on a designated output medium (49) is disclosed which maps colors to the gamut (44) of the designated output medium (49) performing gamut mapping (FIG. 9) earlier in the image synthesis process than current gamut method methods, at the point where information about object primitives and their spectral attributes in a scene description is available, but after the fixed scene geometry has been determined by the rendering system. The method makes use of the output of a symbolic rendering system which produces symbolic pixel expressions (80), having basis spectra variables which represent the interplay of light and object primitives in the scene description, and spectral data (84) having colour information about the light and object primitives in the scene, and which is indexed to the basis spectra variables. The method performs spectral change calculations (90) using the symbolic pixel expressions (80), the spectral data (84), and spectral information about the gamut (44) of the specific output medium (49) to determine the modifications (86) to the original spectral data that need to be made to the individual object primitives in the scene in order to produce image pixel colours which are in the gamut (44) of the output medium (49). The resulting image colours are locally and globally consistent with the semantics of the image, make effective use of as much of the available gamut of the display device as is possible, and require no further post-rendering gamut mapping prior to display or reproduction on the designated medium.

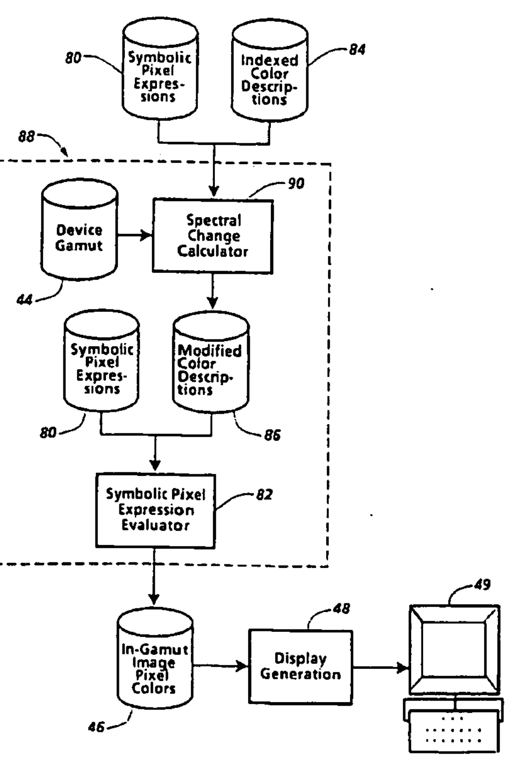

FIG. 1

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The present invention relates generally to the field of computer graphics software and to the rendering of computer-synthesized color images, and more particularly to a method for rendering computer-synthesized color images having image colors which are in the color gamut of a designated output medium, and a machine for implementing such a method.

Computer graphics software and rendering systems provide for the computer synthesis and reproduction of realistic color images and are capable of producing images that include the entire range of visible colors. The broad functions of the typical, computer-based image creation process are illustrated in, and described with reference to, FIG. 13 of USSN 07/965,685 (hereafter "Ref. 1"), a copy of which was filed with the present application. As a scene is constructed by the scene designer, an application-specific model captures data about object primitives, and relationships among them, that comprise the scene, in box 20. The scene description, stored in an application database 22, contains descriptions of primitives that define the shapes of components, objects, and light sources in a scene, appearance attributes of the primitives such as color, and surface texture, and connectivity relationships that show how object primitives are positioned and fit together in the scene. The scene description must then be converted into the set of image pixels for display of the image on an output medium, typically on a monitor or in hardcopy form. The process of mapping the scene description to an image pixel file is typically referred to as "rendering", and the implementation of rendering is referred to as "the renderer", shown in FIG. 13 of Ref. 1 by dotted line box 24.

As can be seen from the functional steps illustrated in FIG. 13 of Ref. 1, any changes that a scene designer may want to make to the image that affect the object primitive level of the image, such as the colours of the objects, will mean changing the scene description database 22 and re-rendering the image, which is a computationally expensive procedure. This includes making changes to the colors of objects in an image, since information about objects, including their colors, is only available in the scene description 22. Alternatively, changes to the image made beyond rendering pipeline 24 must be made at the pixel level. Manually changing object or light source colors at the pixel level, while still maintaining the image realism, is difficult for the scene designer to accomplish accurately.

In another computer-based image creation process, a scene designer is permitted to manipulate scene description colors, surface properties, and light intensities without the computational expense of re-rendering the entire image. This method is described in detail by Carlos H. Sequin and Eliot K. Smyrl in "Parameterized Ray Tracing", Proceedings of SIGGRAPH 1989, July 31 - August 4, 1989 Boston Mass., in *Computer Graphics* 23 (July 1989), pp. 307 - 314, (hereafter, "Séquin"). That method is illustrated in, and discussed in detail with reference to, FIG. 1 of Ref. 1. Briefly, the method modifies a conventional ray tracing program of the type which could be used in shaded rendering process 30 of FIG. 13 of Ref. 1, to produce a parameterized, or symbolic, expression for each pixel as the scene is rendered. Rendering system 25 in FIG. 1 of Ref. 1 utilizes this modified symbolic shaded rendering process to produce a symbolic pixel expression for each pixel in the rendered image.

All of the colors physically producible on a particular color output medium is called the color "gamut" of the medium. The color gamut of an existing output medium is typically smaller than the set of all visible colors which are possible in a rendered image. Moreover, the scene description is typically created independently of the output medium on which it is subsequently displayed or reproduced. The algorithms used in shaded rendering process 30 for modeling the light striking a particular point on an object may very well generate a value for the color of one of the object's pixels that is not within the range of the valid values in the color gamut of the output medium, or that numerically represents a non-visible color, such as a negative value. In most instances, a "gamut mapping" process 40 is necessary to make sure that the color attribute for each pixel in the image is displayable or reproducible on the device selected for display or reproduction. Gamut mapping process 40 is described in more detail below, in conjunction with the discussion accompanying FIG. 1 of Ref. 1.

The technique of producing symbolic pixel expressions illustrated in FIG. 1 of Ref. 1, while significantly reducing the time involved in changing colors and light intensities in a scene, may still produce final image pixel colors which are outside the gamut of the output medium which will display or reproduce the image, since the image is created independently of the output medium on which it is subsequently displayed or reproduced. Thus, as shown in FIG. 1 of Ref. 1, the pixel colors of image pixel file 32 most likely will need to be mapped to the specific color gamut of the output medium, in gamut mapping process 40, before display or reproduction.

Gamut mapping process 40 includes gamut mapping step 42 which applies information about the available color gamut of the output medium from device gamut data file 44 to automated mapping algorithms in order to bring out-of-gamut pixel colors inside the device gamut. Typically, device gamut data file 44 is comprised of data from a sample set of actual colors from the color gamut of the output medium which have been physically measured by an appropriate instrument, such as a colorimeter or spectrophotometer. The output of gamut mapping step 42 is a modified set of image pixel colors, shown in data file 46, that are now in-gamut for a particular output medium. Since each device gamut is different, a new set of image pixel colors is created by the auto-

mated gamut mapping process for each output medium on which the image is to be displayed or reproduced.

The goal of gamut mapping is to fit the image colors into the gamut of the output medium while maintaining overall appearance of the image. The gamut mapping process has generally been the concern of those involved in the reproduction or display of color images, and typically has not been a processing goal of the graphics rendering pipeline 24 (FIG. 13 of Ref. 1) or symbolic shaded rendering system 25 (FIG. 1 of Ref. 1), nor a primary concern of the scene designer. It is a post-rendering step, accomplished typically by using various automated methods implemented in software which globally or locally modify individual pixel colors without regard to the objects in the image from which the pixels are derived. Gamut mapping may also be accomplished manually. Typically, the gamut of the output device is mathematically represented as a three-dimensional volume in a color space, and pixel colors are presented as points in the color space. One common automated gamut mapping method is a "uniform global scaling" of all of the pixels in the image such that the pixel colors most outside the gamut volume of the device are brought within the gamut region in the color space, and all other pixel colors are scaled in proportion. Uniform global scaling is conceptually similar to "turning down the light" in the scene description. In some, or perhaps many, cases, global scaling of the image pixel colors darkens and desaturates the resulting image unacceptably. Another common automated gamut mapping method involves the "local correction" of pixels, where each pixel is independently examined and brought into the gamut of the specific display device on which the image is to be produced. One undesirable effect of most methods of modifying the out-of-gamut pixels alone, apart from the objects in the scene, is the introduction of shading artifacts into the image.

Another highly undesirable effect of all gamut mapping done at the pixel level is to produce an image which is no longer semantically consistent with the interplay of light with objects in the scene. The concept of image semantic inconsistency and problem with the existing process of modifying individual image pixels of objects having out-of-gamut colors is discussed in detail in Ref. 1 with reference to FIG. 2 thereof.

For example, in a synthesized image containing several brightly coloured objects and also containing reflections (56 and 58) of these objects in a window (55), generated by rendering pipeline 24 (FIG. 13 of Ref. 1), the colours of the reflected objects are semantically consistent colours of the "real" objects. If the colours of the real objects are not in the gamut of a particular output device, correcting the colours using uniform global scaling of the image pixel colors will darken both of the objects as well as their reflections, and darkening of the reflections may result in considerable loss of object detail. It is found that local correction of only the out-of-gamut (red) pixels of a certain object (truck 52) to bring them within the gamut of the device will result in a semantically inconsistent image where the reflections of the object reflect a different relationship between the relative brightness of the objects than what is seen between the objects themselves, once corrected for out-of-gamut colors. Alternatively, after the rendering of the image is completed, a user might manually control parameters in automatic mapping algorithms in order to adjust, through trial and error and using artistic judgment, the individual out-of-gamut pixel colors for each of the pixels in the image in order to bring the pixel colors in-gamut in a manner which achieves or almost achieves semantic consistency. This solution, however, rarely provides image semantic consistency because of the complexity of the task, and requires a manual adjustment step which typically involves considerable trial and error because of the relatively unpredictable nature of the changes involved. Thus, semantic inconsistency resulting from a post-rendering gamut mapping process can arise in most rendered scenes which model diffuse and specular inter-reflection of light in the scene.

One method for achieving both in-gamut pixel colors and semantic consistency of object colors and lights in the image for the device on which the image is to be displayed or reproduced, is for the scene designer to try to make color changes to the objects in the original scene description database in order to bring the out-of-gamut colors of certain objects in gamut. If the scene designer is using a symbolic rendering system, such as the one illustrated in FIG. 1 of Ref. 1, re-rendering the scene would not be necessary, but manual adjustments to the colors in the scene would still be required. While this solution of changing the scene description produces semantically consistent images, it requires the manual adjustment of the scene description or the symbolic pixel expressions, which can be a time consuming process, especially if re-rendering is involved.

Because the spectrum, or color description, for one object or light primitive in scene description 22 (FIG. 2) may appear in more than one symbolic pixel expression 80, a modification to one color description may correct some out-of-gamut pixel colors while producing other pixel colors which were formerly in-gamut but become out-of-gamut as a result of the modification. Thus, the problem of directly modifying the original color descriptions to produce an in-gamut image is typically more complex than simply bringing all of the color descriptions into the gamut of the selected output device. In addition, any single set of modifications directly to the original color descriptions could produce an image having all in-gamut pixel colors, but that image may not satisfy the image metric.

What is needed, therefore, is a method of rendering a color image with semantically consistent object colors that are always within the measured gamut of the specific output medium on which the image is to be re-

produced or displayed, thus avoiding both the manual and automatic correction of image pixel colors which introduce image and object semantic inconsistencies during post-rendering pixel color adjustments.

The present invention provides a method of rendering a colour image from symbolic image data, according to claim 1 of the appended claims.

The method of the present invention, in particular, is a device directed method of performing the gamut mapping process 40 of FIG. 1 of Ref. 1 earlier in the image synthesis and rendering process, at the point where information about object primitives and their color attributes in a scene description is available, but after the point where the fixed scene geometry has been determined by a conventional rendering method. Preferably, the method uses the symbolic color image data and the color description data which are the output of a symbolic shaded rendering system. The symbolic color image data, in the form of symbolic pixel expressions, directly represent the interplay of light and object primitives in the original scene description. The color description data contain the light intensities and colors of the object primitives in the scene, which have been separated from the scene geometry itself, but which are associated with the symbolic color image data via unique identifiers such as indices. The method of the present invention is premised on the discovery that, since the light and color values have been separated from the scene geometry, they are available for modification with respect to the color gamut of a particular color reproduction device, and the effect on the original scene of every modification made to the the light and color values will be captured in the terms of the symbolic expressions. Thus, the method also uses device color data which represents the color gamut of the color output medium. Using the symbolic color image data, the indexed color description data, and the device gamut data, the method performs spectral change calculations to determine modifications to the indexed color description data that produce colors which are in the gamut of the color output medium, and which, when used with the symbolic color image data in a later step, will generate a target color image where each target color is one of the device colors in the gamut of the color reproduction device. Because the symbolic pixel expressions 80 maintain picture information in a symbolic form at the object primitive level, any changes to the colour and light intensity values which are substituted in the terms of the expressions result in changes at the object level in the colour image, thus changing not only object colours, but also changing the portions of the image that are affected buy the changes in object colours. This occurs because the method 90 of the present invention simultaneously changes all of the appropriate symbolic color terms wherever they occur in the symbolic pixel expressions 80. All image pixels which have light contributions from an object primitive with a changed colour value are thus changed, and the image remains semantically consistent while the colours are brought in gamut for the designated output me

The method of the present invention thereby preserves semantic image consistency in each rendering, without the need to re-render the image, by utilizing the symbolic pixel expressions and associated color descriptions to represent information about object primitive relationships in the rendered color image, and produces image pixel colors which make effective use of as much of the available gamut of the display device as is possible, and require no further post-rendering gamut mapping prior to display or reproduction of the image. In addition, the automated process of producing semantically consistent, in-gamut images can simply be performed again to reproduce or display the image another time on the same device, without the need to repeat time-consuming manual adjustments to pixel or scene object colors.

The method of the present invention produces a semantically consistent rendered color image and maintains this image semantic consistency while the final image colors are brought within the gamut of the designated output medium, without the computationally expensive step of re-rendering the image or the time-consuming post-rendering step of manual pixel color adjustment. Because the symbolic pixel expressions 80 maintain picture information in a symbolic form at the object primitive level, any changes to the color and light intensity values which are substituted in the terms of the expressions result in changes at the object level in the color image, thus changing not only object colors, but also changing the portions of the image that are affected by the changes in object colors. This occurs because the method 90 of the present invention simultaneously changes all of the appropriate symbolic color terms wherever they occur in the symbolic pixel expressions 80. All image pixels which have light contributions from an object primitive with a changed color value are thus changed, and the image remains semantically consistent while the colors are brought in gamut for the designated output medium. Utilizing the method of device directed rendering for rendering the image 50 of an outdoor street scene in FIG. 2 for a particular output medium would result in bringing the red pixels of bright red fire truck 52 into the gamut of the output medium, while also maintaining the brightness relationship between fire truck 52 and construction cone 54 in the colors of their reflections in the window 55.

In another aspect of the present invention, there is provided a method of rendering a colour image from symbolic image data according to claim 4 of the appended claims.

In particular, and more preferably, the method comprises the steps of assigning change variables, or weights, to the symbolic color image data, each change variable having a current value; evaluating the sym-

bolic color image data with the indexed colour description data indexed to respective ones of the symbolic colour image data to generate a current color image composed of current colors, the current values for the change variables being applied to the indexed colour description data items indexed by the respective symbolic colur image data items; and generating a target color image composed of target colors from the current colors of the current color image using the device gamut color data representing a gamut of device colours of a colour reproduction device; each of the plurality of target colours composing the target colour image being one of the device colours in the gamut and corresponding to one of the current colours of the current colour image. Then, calculating difference data between the current colors and the target colors is calculated. Using the difference data, incremental change quantities for the values of the change variables are determined in order to find the next set of values for the change variables. A test is then made to determine from the difference data and from the incremental change quantities whether the current color image satisfies image metric data. The image metric data includes relationship data for measuring a valid color image in terms of a relationship between the current color image and the target color image, and change variable data for measuring a minimum acceptable quantity for the incremental change quantities. If the current color image does not satisfy the image metric data, then the incremental change quantities are applied to update the current values of the change variables, and the above steps are repeated again, as long as the image metric is not satisfied. Once the image metric is satisfied, the current values of the change variables assigned to the symbolic color image data are applied to the corresponding indexed color description data to produce the modified color description data.

In accordance with another aspect of the present invention, there is provided a method of operating a machine for rendering a colour image from symbolic image data, according to claim 6 of the appended claims. Preferably, stored in the memory include mathematical operators combining the symbolic spectral components into a single symbolic expression.

Preferably, the step of determining a new value for at least one change variable includes the steps of (b.1) determining an incremental change quantity from a current value of the change variable; and b.2) applying the incremental change quantity to the current value of the change variable to obtain the new value.

Preferably, each symbolic color image data item includes a symbolic pixel function of the change variables and the symbolic spectral components; and the step of determining an incremental change quantity includes the steps of (i) differentiating each symbolic pixel function with respect to the change variables therein to produce differentiated symbolic pixel functions; (ii) constructing a jacobian matrix in the memory of the machine from the differentiated symbolic pixel functions; (iii) computing and store in the memory of the machine a pseudo-inverse jacobian matrix from the jacobian matrix; and (iv) evaluating the pseudo-inverse jacobian matrix using the current value of each change variable to find the incremental change quantity for each change variable.

Preferably, the desired relationship represented by the image metric data is a distance quantity in a color space between each of the image pixel color data items composing the color image and a corresponding one of the target image pixel color data items; and the color image satisfies the relationship represented by the image metric data when the distance quantity is minimized.

Preferably, the method further includes after step (a) and before step (b), the steps of (a.1) initializing the change variables with initial values having no modification effect on the symbolic spectral components; (a.2) evaluating each symbolic spectral component of each symbolic color image data item with the indexed color description data items to produce a plurality of ideal image pixel color data items composing an ideal color image; and (a.3) storing the ideal image pixel color data items in the memory; and wherein the image metric data represent a desired relationship between the plurality of ideal image pixel color data items composing the ideal color image and the target image pixel color data items composing the target color image.

The present invention further provides a programmable image processing device when suitably programmed for carrying out the method of any of claims 1 to 7 or any of the above-described particular embodiments.

In accordance with still another aspect of the present invention, there is provided a machine for rendering a colour image from symbolic image data, according to claim 8 of the appended claims.

In summary, the method of the present invention modifies individual object and light source scene spectra in order to produce a rendered color image having colors that are directly displayable or reproducible on a selected output medium without an additional gamut mapping step applied to individual image pixels. The image produced by the method preserves semantic relationships and consistency among the objects in the image while taking advantage of the widest range of colors available in the output medium's gamut. By changing the scene description rather than individual image pixels, the introduction of shading artifacts is avoided, and changes in the relative brightness of objects and in pixel chromaticity, in certain instances, are permitted.

Other aspects of the present invention will become apparent as the following description proceeds and upon reference to the drawings, in which:

Figure 1 is a block diagram illustrating the data flow for color image rendering using the method of device

directed rendering according to the present invention;

Figure 2 is a block diagram illustrating the functional steps for the method of device directed rendering shown as block 90 in FIG. 1;

Figures 3 and 4 diagrammatically illustrates using weighted vectors according to one embodiment of the present invention to represent colors in a color space, and modifying the weights to change the colors;

Figures 5, 6, 7 and 8 conceptually illustrate a model of an image, or picture, function used according to an embodiment of the method of the present invention;

Figure 9 is a flow chart illustrating the steps of one implementation of the method of the present invention;

Figures 10, 11 and 12 are block diagrams of suitable machine configurations which may be operated according to the present invention;

Figure 13 illustrates schematically representative data structures used by the present invention;

In the Figures, the same numbers have been used to denote the same elements.

In FIG. 1, the device directed method for rendering a color image, illustrated as spectral change calculator 90, uses as input the original color and light intensity values for the scene description in indexed color description data 84 and symbolic color image data, called symbolic pixel expressions 80, both generated by a rendering system, and device gamut color data 44, defining the colors capable of reproduction by color device 49. The method performs spectral change calculations to produce as its output, a set of modified color descriptions 86 which are modified color and light intensity values for the scene description. When the modified color descriptions 86 are used, along with the symbolic pixel expressions 80, in the symbolic pixel expression evaluator 82, image pixel color data 46 composing a color image is produced which has pixel colors which are substantially all in the device gamut of device 49. The modified color description data 86, together with the symbolic pixel expressions 80, now represent the color image rendered for device 49, and no gamut mapping step prior to display or reproduction is needed to ensure displayable colors on output medium 49. It is not necessary to perform evaluation step 82, however, until a user or viewer of the color image is ready to display or reproduce the image.

FIG. 2 illustrates the broad steps of performing the spectral change calculations. Each of the originally defined color and light intensity values for the scene description 22 in indexed color description data 84 is modified, in box 94. The details describing one way in which the color descriptions are modified is set forth below, with respect to the illustrated embodiment. Generally, the color descriptions must be modified in a manner which, when all of the modified color descriptions are evaluated in the symbolic pixel expressions 80 to produce a color image for display, in symbolic pixel expression evaluator 82, the color image which is produced by symbolic pixel expression evaluator 82 is composed of pixel colors in the device gamut 44 of device 49. Typically, the color descriptions will be modified in a manner which results in the modified color being in device gamut 44, although they may be adjusted to meet other similar criteria. The modifications need not be directly made to the values of the original colors in indexed color description data 84. Since the original colors are indexed to and represented in the symbolic pixel expressions, manipulations of the symbolic color terms in the symbolic pixel expressions, which result in modifying the values of the color descriptions when they are substituted in the symbolic pixel expressions, may also accomplish the necessary modifications indirectly.

Once a first set of modifications to the indexed color description data 84 has been made, the modified color descriptions are evaluated, in box 82, in the symbolic pixel expressions 80 to produce a color image

In box 100, each image pixel color in the color image is mapped to the device gamut of a specific display or reproduction device (shown as device 49 in FIG. 1) using a conventional gamut mapping process. Typically, the device gamut of a device is conceptually and mathematically represented as a three-dimensional volume in color space, and a mapping process finds a desirable replacement color in the device gamut for the out-of-gamut color, according to a mathematical algorithm for finding a desirable replacement. The device gamut, however, may also be represented in other ways, such as, for example, as simply a look-up table of measured color values for valid device colors. Device gamut data 44 include the data needed to represent the gamut in the manner selected by the implementation. The act of mapping each pixel color in the current color image to the device gamut using device gamut data 44 generates a target color image having all pixel colors in the gamut of device 49.

The inquiry in box 96 tests whether the target image generated in box 100 satisfies an image metric which measures whether the target image is a valid target image. The image metric, in its simplest form, may simply require that all evaluated symbolic pixel expressions 80 produce in-gamut pixel colors. However, there may be many modifications to the original color descriptions in indexed color description data 84 which would produce one or more color images having substantially all pixel colors in the device gamut represented by device gamut data 44. The image metric may determine which one or ones of the possible target color images are valid target color images. The image metric may also provide for modifications to the color descriptions to stop within a certain number of processing cycles (in which case any remaining out-of-gamut pixel colors will remain

out-of-gamut).

The determination of validity of a target color image may be established in a number of ways, and a specific image metric is described in more detail below with respect to the illustrated embodiment. Generally, the goal of the device directed rendering method of the present invention is to find a set of color values for the colors of the objects and lights in the rendered image which are in the device gamut represented by device gamut data 44, and which produce an image which is acceptable, for some measurement of "acceptable". Thus, the validity measurement of the image metric is typically a measurement of target color image acceptability to the user of the method. In one embodiment of the method, the acceptability measurement of the target color image is stated in terms of, or as a function of, the original color image rendered by the rendering system. An original color image, also called an "ideal" color image, may be generated by evaluating (using symbolic pixel expression evaluator 82) the symbolic pixel expressions with the original indexed color descriptions 84, prior to modification, and each target color image generated may be compared in some manner to the ideal color image to determine validity as a measure of whether the target color image is an acceptable substitute for the ideal color image. The image metric may also, for example, or provide a measurement of the perceptual suitability of an arbitrary image as a substitute for the original, ideal image.

If the image metric has been satisfied, the indexed color descriptions as currently modified are the color descriptions to be saved as in-gamut color description data 86 (FIG. 1). The modified, in-gamut color descriptions 86 are the set of color descriptions which produce an in-gamut target picture which satisfies the measurement expressed in the image metric, and which, together with the symbolic pixel expressions 80, produce the valid in-gamut target picture.

If, however, the modified color descriptions do not produce the in-gamut target picture which satisfies the image metric, the process flow returns to repeat the modification, evaluation, and mapping steps. It may be possible, in a particular implementation of the method steps illustrated in FIG. 2, to simultaneously modify all of the indexed color descriptions that require modification to produce the target color image which satisfies the image metric. In that implementation, the image metric would be satisfied with the first target color image produced from modified color descriptions, and the method would terminate without repeating steps 94, 82, and 100.

The method of the present invention begins with the output generated by a symbolic rendering system: the symbolic pixel expressions 80 and the indexed color descriptions 84. The creation of the scene and the scene description database are accomplished in the same manner as described in Ref. 1 with reference to FIGS. 12 and 1 thereof, utilizing known modeling, painting, or other software tools for creating images. The scene description contains descriptions of primitives that define the shapes of components, objects, and light sources in an image, appearance attributes of the primitives such as transparency, color, and surface texture, and connectivity relationships that show how objects are positioned and fit together in the image. In the illustrated embodiment, each color of an object surface or illuminant in the scene description that is the input to the symbolic rendering system is represented as a single spectral function of wavelength. For an illuminant, the spectrum represents the amount of power at each wavelength; for a surface, the spectrum represents the amount of incident light reflected at each wavelength. However, the method of the present invention is intended to also cover other illumination and reflection models.

In the illustrated embodiment, the scene description is provided to a symbolic rendering system which uses a modified ray tracer to produce an image, or picture, in symbolic form having one symbolic pixel expression 80 for each image pixel. The ray tracing method assumed one ray per pixel. The method of the present invention, however, is suitable for use with other rendering models, shading equations, and screen sampling patterns.

An indexed is assigned to each unique color in the scene, from both illuminants and surface reflections. The indices along with their associated color descriptions (spectra) are output, either as a separate file of indexed color descriptions 84 as shown, or as part of the file of symbolic pixel expressions 80. FIG. 13 illustrates a representative structure for the file 84 of data items comprising the indexed color descriptions. The number of indexed color description data items depends on the number of unique color and light intensity values that exist in the scene description. A single indexed color description data item 262 is composed of an index field 264 and a color, or spectrum, data field 266 containing color information. In illustrated data field 266, the color information is represented as RGB information, but any data format suitable for representing and encoding color information may be used. In the implemented embodiment, the color information is represented as an array of floating point numbers defining a color as a set of spectral samples.

Each symbolic pixel expression represents all of the color contributions from objects and lights in the scene at that pixel, or, more precisely, the sum of the combined diffuse and specular reflections of the light propagated from the surface of an object to the observer's eye. To produce the symbolic pixel expressions 80, the symbolic rendering system multiplies together the spectra of the scene surfaces and the lights to form the

components, or terms, of the symbolic expressions 80, called "basis spectra", which in turn are added to produce the color at each pixel. Each basis spectrum component term in a single expression also has an associated constant that depends on the geometry of the intersection and properties of the surface. Specifically, the expressions are made up of real numbers, arithmetic operators, parentheses, and color symbols (spectral references), as described in Sequin. For example, a color with the index of 3 may be referenced in a symbolic pixel expression simply as "s3". The parameters in each expression, when evaluated with actual color values, such as those provided in the original scene description 22, together define the spectral power density (SPD) of incident light at an image pixel.

An example of how a symbolic pixel expression of component basis spectra terms is constructed by the symbolic rendering system illustrates this process more clearly. Assume that a scene description 22 consists of one illuminant with a spectrum designated as $S_1(\lambda)$, and one surface with spectral reflectance function $S_2(\lambda)$, where λ denotes wavelength. $E(\lambda)$ denotes the spectrum of a pixel that receives a ray that carries light from the illuminant and is reflected from a plastic surface into the pixel. The simple shading model of the renderer produces a relationship of the form:

$$E(\lambda) = c_1 S_1(\lambda)\, S_2(\lambda) + c_2 S_1(\lambda) \quad (1)$$

where the c_1 and c_2 are the scalar constants which are functions of the relative geometry of the illuminants and surfaces and the physical properties of the surfaces. Note that scalars c_1 and c_2 are important for rendering the final image and are shown for completeness, but are not important to the method of the present invention. The two terms on the right hand side of Equation (1) correspond to the diffuse and specular components of the light reflected from the plastic surface provided as the example. In more complex scene instances, additional "bounces" of a ray through the scene (i.e., the levels in the ray tree constructed by the ray tracer) results in additional spectra being multiplied together, resulting in turn in a high-order polynomial in the spectra. Actual experience with the implementation of the present illustrated embodiment shows that the ray tree usually does not exceed two or three levels, which prevents the order of the polynomials at the pixels from rising too high.

FIG. 13 illustrates a representative data structure for symbolic pixel expression file 80. A single symbolic pixel expression 252, representing the color information for a single pixel in the color image, is composed of basis spectra terms 254 and arithmetic operators 256. Each basis spectra term 254 includes one or more data areas 258 for data produced by the symbolic rendering system not directly related to spectral data, such as the scalars c_1 and c_2 discussed above, and one or more symbolic spectral components 260 which are, in effect, indices into indexed color description data items 84. The use of an indexing scheme to create indirect referencing between a symbolic pixel expression 252 and color description data 84 is an efficient implementation over using actual color description data in the symbolic pixel expressions, and as noted earlier, any suitable indirect referencing arrangement may be used for associating the actual color and light intensity values in color description data 84 to the corresponding symbolic spectral components in the symbolic pixel expressions. The symbolic spectral components 260 are used for indexing into the indexed color description data 84, as shown by arrow 268, to retrieve the corresponding color information data, or spectrum data, needed to evaluate the symbolic pixel expression to produce the image pixel color.

The basis spectra terms in each symbolic pixel expression are preferably converted to tristimulus values describing vectors in tristimulus space using a "tristimulus operator", T, such that $T[E(\lambda)] = \mathbf{x}$, where $\mathbf{x}$ is the three-vector containing the tristimulus values XYZ corresponding to $E(\lambda)$. If $T[S_1(\lambda)S_2(\lambda)] = \mathbf{x}_{12}$ and $T[S_1(\lambda)] = \mathbf{x}_1$, then applying the tristimulus operator to both sides of Equation (1) yields a linear combination of tristimulus vectors:

$$T[E(\lambda)] = T[c_1 S_1(\lambda)\, S_2(\lambda) + c_2 S_1(\lambda)] \quad (2)$$
$$\mathbf{x} = c_1 T[S_1(\lambda)\, S_2(\lambda)] + c_2 T(S_1(\lambda)] \quad (3)$$
$$= c_1 \mathbf{x}_{12} + c_2 \mathbf{x}_1 \quad (4)$$

When this conversion is performed is an implementation decision, and the basis spectra terms may be converted to tristimulus vector terms by the symbolic rendering system, after the ray tracing step, as in the illustrated embodiment, or later, as an initial process in device directed rendering step 90. The final color of each pixel in the rendered image is thus defined, in the symbolic pixel expression, as the sum of one or more of the tristimulus vector terms. In the illustrated embodiment, then, color representation and manipulation is performed in the tristimulus color space model. Color representation and manipulation may also be carried out in other color spaces, since the tristimulus vectors may be converted further into other color models such as CIE color space models, and the RGB or HSV color models, through mathematical conversions well known in the art. Additional processing considerations must be taken into account, however, if a color space is used which is a nonlinear transformation away from the tristimulus color space model.

The illustrated embodiment of the present invention is based on mathematical models shown in FIGS. 3 to 8. The implementation of the mathematical models is handled as an optimization problem. Determining modifications to the original color descriptions in an efficient manner requires finding a set of optimal modifications

to make to one or more of the color descriptions simultaneously which both produce an in-gamut, or target, color image and which is a valid target picture as defined by the image metric. Since, when suitable color descriptions are substituted for the symbols in the basis spectra terms, the symbolic pixel expressions ultimately determine all of the image pixel colors, the modifications to the original color descriptions can be efficiently determined indirectly, by manipulating the symbols representing the original color descriptions in the basis spectra terms in such a manner as to be able to apply the manipulations to the original color descriptions to determine the modified color descriptions.

The mathematical model of the illustrated embodiment, to be described in detail below, is summarized as follows. The model defines an original rendered image, also known as the ideal image, as a "picture" represented in "picture space". The picture is defined as a function of the basis spectra (color descriptions 84). Each spectrum may be scaled by a weight to adjust its color. Because the spectra are physical representations of colors, the weights must meet certain criteria, and so, of all weights in "weight space", there is subset of weights which are valid. The subset of valid weights when applied to the spectra produce a subset of valid pictures in picture space. Because a picture is a function of the spectra, and each spectrum is a function of one or more weights, a valid picture may be expressed as a continuous function of the weights, and the subset of valid pictures define a subset in picture space. A device gamut also defines a subset in picture space. A "target picture" is defined as a picture which has image pixel colors that are reproducible colors in the device gamut. The target picture may be found by applying a gamut mapping function to the original ideal image. There is some set of weights which meet the following constraints: the set of weights produces a valid picture in picture space; the picture produced is also in the device gamut of picture space; and the picture produced meets some objective function, called the image metric or "goodness function" which describes the desired relationship between the original picture in picture space and a target picture in the gamut subspace of picture space. Optimization of this mathematical model attempts to find the optimal set of values for the weights that are needed to meet these constraints. The details of this model follow.

As noted above, in each symbolic pixel expression, tristimulus vector terms represent individual color contributions from object and light primitives in the scene to the final pixel color represented by the expression. The tristimulus vector terms, in turn, were converted from basis spectra, and so represent the scene spectra (objects and lights) which affect the color in the particular pixel represented by the expression. Typically, the basis spectra occur as terms in multiple symbolic pixel expressions, because the lights and the objects in the scene influence the color in many individual pixels.

Figures 3 and 4 illustrate the concept of basis spectra as vectors in the color model known as tristimulus space. Note that FIGS. 3 and 4 illustrate a two-dimensional example, simplified from the three-dimensional model implemented in the illustrated embodiment, and that the vectors shown demonstrate only one of the possible symbolic expressions for a pixel. In FIG. 3, dotted line box 120 represents the volume of tristimulus space. Within tristimulus space 120, a subset 122 of tristimulus space represents the gamut of a particular output medium, also denoted"G" in FIG. 3. The color of a light source, L, in the image to be rendered is represented by the vector in tristimulus space 120 denoted S_L. Similarly, the color of a surface, S_S, illuminated by light source, L, in the image is represented by the product of S_S and S_L, denoted S_SS_L. A pixel 124 in the image has a color which is determined by the sum of S_SS_L and S_L. Pixel 124 happens to be outside of gamut 122.

For the case where the color of any pixel in the rendered image is out of gamut, the individual scene spectra, S, for either the object surfaces (S_S) or the light intensities (S_L), or both, in the symbolic pixel expression which generated the out-of-gamut pixel, are adjusted, or scaled, by a weight, w, in order to bring the vectors representing the scene spectra closer to the volume bounded by gamut G. In an initial processing step of device directed rendering method 90, each spectral function $S_i(\lambda)$ (an original color description symbol or index) in Equation (1) is replaced with $w_iS_i(\lambda)$, a weighted color description symbol or index. Applying the tristimulus operator T to both sides of Equation (1), as done above in Equations (2), (3), and (4), yields:

$$\mathbf{x} = (c_1\mathbf{x}_{12})w_1w_2 + (c_2\mathbf{x}_1)w_1 \quad (5)$$

Because **x** is a tristimulus vector, Equation (5) defines three equations, each a polynomial in the weights.

Figure 4 illustrates how individual weights applied to scene spectra bring individual pixels into the gamut of the output medium. Pixel 124 and gamut 122 are shown in the same positions they have in tristimulus space 120 of FIG. 3. In the illustrated embodiment, a pixel defined by a single vector can only be brought into gamut if the line along the vector intersects the device gamut. Thus, if the pixel color at point 124 in tristimulus space were defined only by a single vector along line 124a, a single weight applied to the vector would not be able to bring the pixel color into gamut 122, since it would scale the color only along line 124a. However, since pixel 124 in FIG. 3 is defined as a sum of vectors, the pixel color can be corrected (i.e., brought into gamut 122) by scaling the weights of the light source and surface spectra as long as the plane or volume bounded by the vectors intersects the device gamut. In FIG. 3, in essence, vector S_SS_L has been scaled with weights having values of one (1). In FIG. 4, two corrections are shown. The basis spectrum of light source, L, has been scaled

by weight wL and the product of the spectrum and the weight results in a new vector in tristimulus space 120, denoted w_LS_L. Weight, w_L, has also been applied to the spectrum of light source L in basis spectrum (product vector) S_SS_L Scaling the spectra with weight w_L will change the pixel value in a manner defined by the rules of vector algebra. Thus, the new product vector in tristimulus space 120 denoted $w_LS_SS_L$ represents a pixel color that has changed from position 124 to position 126 in tristimulus space. Because only a single weight has been applied, the scaling results in pixel color 124 changing along line 124a to point 126, toward the origin point of gamut 122. In effect, such a change only results in changing the brightness of the pixel color, and not its chromaticity. Pixel color 126 is closer to the boundary of gamut 122, although it is still an out of gamut color. Applying weight w_S and scaling the spectrum of surface S_S results in a new product vector in tristimulus space 120, denoted $w_Sw_LS_SS_L$, representing a new pixel color 128 in tristimulus space which is now within the boundary of gamut 122. Pixel color 128 is now capable of reproduction in the selected output medium represented by gamut 122.

In the weight system of the illustrated embodiment, there is a single weight for each spectral function, and each weight must meet certain constraints. If the total number of weights is ***M***, each weight is mathematically represented as a component of ***M***-dimensional vector, **w**. A particular set of weights defines a point in an ***M***-dimensional Euclidian "weight space". Because the spectral functions have a physical interpretation, they cannot be scaled arbitrarily. The weight that scales a spectral function must be chosen so that the scaled spectral function is physically realizable. In general, weights are positive and nonzero. Surface reflectance functions cannot have values greater than 1.0. **W** denotes the subset of ***M***- dimensional weight space containing all possible **w**'s that produce physically realizable scaled spectral functions.

Figure 13 illustrates a representative data structure for a single symbolic pixel expression 270 scaled with weights. A single unique weight 272 is assigned to each symbolic spectral component 260 in expression 270. As a weight takes on values, it functions as a multiplier on the symbolic spectral component 260 to which it is assigned. In turn, the multiplier is applied to the actual color information 266 in indexed color description data 84 when symbolic spectral component 260 is used to index into indexed color description data 84 during evaluation of expression 270.

Figures 5 to 8 conceptually illustrate the mathematical model of the problem statement. The N image pixel colors which result from evaluating the symbolic pixel expressions 80 each have three tristimulus values per pixel, and are collectively designated as a "picture" in "picture space". The N image pixel colors of the picture are represented by vector **p**. Vector p is a long vector comprised of 3N tristimulus values, built from a picture in scan-line order, and p_i denotes the i^{th} component of **p**, corresponding to one tristimulus value at one pixel. The set of image pixel colors evaluated from the symbolic pixel expressions 80 with the current object and light intensity values is designated as the picture, $\mathbf{p}_0$. Since the spectra are functions of the weights, and the picture is a function of the spectra, a picture function, *f*, is defined which maps weights to tristimulus values in pixels. The picture function is denoted as $\mathbf{p} = f(\mathrm{w})$. *P* is the subset of "picture space" containing all pictures for which there exists a weight vector **w** in weight space W such that $\mathbf{p} = f(w)$. The picture function is vector-valued, and f_i denotes the i^{th} component function of **p**. Each component function is a low-order polynomial function in the weights, as illustrated by Equation (5), and thus is continuous and has easily computable derivatives of all orders.

A linear approximation to the picture function is developed which is used to search for the optimal set of weights to bring the picture into gamut. The matrix of first partial derivatives of the picture function, $f(\mathbf{w})$, is a Jacobian matrix having dimensions of 3N x M, where the entry on the i^{th} row and j^{th} column is the partial derivative of f_i, with respect to w_j (the jth component of **w**). This Jacobian matrix is denoted J_f. Because *f* is nonlinear, J_f will depend on **w**.

The linear approximation to $\mathbf{p} = f(w)$ is formed by truncating the Taylor series expansion of *f* after the second term:

$$p + \Delta p = f(w + \Delta w) \quad (6)$$

$$p + \Delta p \approx f(w) + J_f \Delta w \quad (7)$$

Because $\mathbf{p} = f(w)$, the approximation that is made is $\Delta \mathbf{p} \approx J_f \Delta \mathbf{w}$.

The linear approximation just described is used to find the changes in the vector of weights, $\mathbf{w}_0$, of the current picture function, $\mathbf{p}_0$, that are needed to satisfy the picture function that represents the target picture, $\mathbf{p}^*$. Target picture $\mathbf{p}^*$ is also a function of a set of weights, designated as target weights $\mathbf{w}^*$, such that $\mathbf{p}^* = f(\mathbf{w}^*)$ The target picture $\mathbf{p}^*$ is produced by mapping the ideal or current picture to the gamut of the device (described in more detail below), so $\mathbf{p}^*$ is not necessarily in *P*, since there may be no $\mathbf{w}^*$ such that $\mathbf{p}^* = f(w^*)$. In the implemented embodiment, the target weights $\mathbf{w}^*$ are defined to be the weights needed to minimize some measure of distance between p* and the picture function $f(\mathbf{w}_0)$. The weights, $\mathbf{w}_0$, are already known, since $\mathbf{p}_0 = f(\mathbf{w}_0)$. Thus, the linear approximation ofthe picture function is used to find the changes in the weights needed to minimize some measure of distance between $\mathbf{p}^*$ and the picture function $f(\mathbf{w}_0)$. This distance is defined as a dis-

tance function, $d(\mathbf{p}^*, \mathbf{f}(\mathbf{w}))$, and is the image metric hereafter referenced as the objective or goodness function, of the optimization problem.

FIG. 5 illustrates the subset P of picture space, a target picture, $\mathbf{p}^*$ which is not in P, and the picture in P, designated by picture function $f(\mathbf{w}^*)$, which is the closest, in Euclidian distance, to the target picture. In the implemented embodiment, the distance function which produced acceptable picture results is defined as:

$$d(p^*, f(w)) = \|p^* - f(w)\|^2 \quad (8)$$

where $\|\cdot\|$ denotes Euclidian distance. Thus, the distance between two pictures is measured by the squared Euclidian distance between them in picture space. Other goodness functions are also possible, and may be preferable to the distance function of Equation (8) for certain images or certain device gamuts. For example, a goodness function which describes the minimum distance from $\mathbf{p}$ to the most perceptually acceptable substitute for $\mathbf{p}^*$ in G is a desirable goodness function.

The gamut of the designated output medium is the region of three-dimensional tristimulus space, denoted G_3, that the device can render. A picture, $\mathbf{p}$, is in gamut when all of its pixels are in gamut. All in-gamut pictures form a subset, G, of picture space P. There exists a "gamut projector" function, h, which maps a picture $\mathbf{p}_0$ to the picture in G "closest" in Euclidian distance to $\mathbf{p}_0$. Figure 7 illustrates picture $\mathbf{p}_0$ and the picture, $h(\mathbf{p}_0)$ in G "closest" in Euclidian distance to $\mathbf{p}_0$ Some picture $\mathbf{p}$ is the picture that minimizes $d(\mathbf{p}_0, \mathbf{p})$ over all $\mathbf{p}$ in G. Note that gamut projector function h is the identity operator when $\mathbf{p}_0$ is already in G:$h(\mathbf{p}_0) = \mathbf{p}$ for $\mathbf{p}_0 \in G$.

Figure 6C illustrates one solution to the stated problem. In the search for the changes to the weights, $\mathbf{w}$, for the picture that minimizes $d(\mathbf{p}_0, \mathbf{p})$ over all $\mathbf{p}$ in G, first the gamut projector function h is applied to the picture $\mathbf{p}_0$ to obtain the target picture $\mathbf{p}^* = h(\mathbf{p}_0)$. By the definition of h, $\mathbf{p}^*$ is in gamut, but it may not be in P. Then, a nonlinear minimization process (described in detail below) is used to find changes in weights, $\mathbf{w}$, which move picture $\mathbf{p}_0$ in P toward $\mathbf{p}^*$. The goal of these two steps is to end at $\mathbf{f}(\mathbf{w}^*)$ which defines the picture in G which is the smallest distance from $\mathbf{p}^*$. Since $\mathbf{p}^*$ is fixed, the distance that must be found depends only on $\mathbf{w}$. In effect, the problem is to minimize a function $g(\mathbf{w}) = d(\mathbf{p}^*, \mathbf{f}(\mathbf{w}))$ with respect to $\mathbf{w}$. The function is nonlinear, and a variety of nonlinear optimization techniques are applicable to the problem.

The problem of finding the optimum set of weights with which to scale the spectra to produce an in-gamut picture can now be briefly restated in the following form. Given an initial picture $\mathbf{p}_0$, and an initial set of weights, $\mathbf{w}_0$, such that $\mathbf{p}_0 = f(\mathrm{w})$, the problem is to find the $\mathbf{p}$ that minimizes the distance $d(\mathbf{p}_0, \mathbf{p})$ over all $p \in P \cap G$. For a picture $\mathbf{p}$ to be in the set $P \cap G$, $\mathbf{p}$ must be in gamut, and there must be a $\mathbf{w} \in \mathbf{W}$ such that $\mathbf{p} = f(\mathbf{w})$.

The specific steps of the implemented nonlinear optimization technique are as follows. When the distance $d(\mathbf{p}^*, f(\mathbf{w}^*))$ is not expected to be too large at its minimum, the Gauss-Newton method may be used to find $\mathbf{w}^*$. The method is discussed by P. Gill, W. Murray, and M. Wright in *Practical Optimization,* at pages 134 - 136. The method produces a sequence of $\mathbf{w}$'s which converge to $\mathbf{w}^*$. At each iteration, the next $\mathbf{w}$ is computed by choosing a direction in which to step w and a length for the step. The Jacobian of f, J_f, is used to compute the step directions, essentially linearizing the problem around the current value of $\mathbf{w}$. Table 1 shows the general steps of the implemented method.

TABLE 1

Steps in Gauss-Newton Method	
1.	Evaluate J_f at $\mathbf{w}_i$, and let $\Delta\mathbf{p}_i = \mathbf{p}^* - \mathbf{p}_i$;
2.	Choose step direction $\Delta\mathbf{w}_i$ to minimize $\|\Delta\mathbf{p}_i - J_f\Delta\mathbf{w}_i\|$ as follows:
	$\Delta\mathbf{w}_i = J_f{+}\Delta\mathbf{p}_i$ where $J_f{+}$ is the pseudo inverse of J_f;
3.	Choose a step length, k, according to an estimate of how nonlinear f is;
4.	Let $\mathbf{w}_{i+1} \leftarrow \mathbf{w}_i + k\Delta\mathbf{w}_i$; let $\mathbf{p}_{i+1} \leftarrow (f(\mathbf{w}_{i+1})$;.
5.	If the sequence $\{p_i\}$ has converged, exit; else let $i \leftarrow i + 1$ and return to step 1.

Figure 8 illustrates that the steps just described alone will not guarantee that the picture which is the smallest distance from $\mathbf{p}^*$ will be in G. Using the two steps just described results in picture $\mathbf{p}_1$ being the closest picture to $h(\mathbf{p}_0)$, but $\mathbf{p}_1$ is not in G. A third step guarantees that the picture which is the smallest distance from $\mathbf{p}^*$ will be in G. At every step in the nonlinear minimization process used to find weights, $\mathbf{w}$, which move picture $\mathbf{p}_0$ in P toward $\mathbf{p}^*$, the target picture $\mathbf{p}^*$ is also recomputed so that there is a sequence of target pictures, $\mathbf{p}_i^* = h(\mathrm{p}_i)$, as shown in FIG. 8. As long as there is some way to move the weights, w, the successive pictures, $\mathbf{p}_i$, in P will continue to move in P toward the recomputed target pictures, $\mathbf{p}_i^*$, into G, ending at $\mathbf{p}_i$ as shown.

It can be seen from the process just described and from its illustration in FIG. 8, that the process implemented in the illustrated embodiment does not necessarily keep the recomputed target picture $\mathbf{p}^*_l$ close to the originally computed target picture $\mathbf{p}^*_0$ in *G*. The final $\mathbf{p}^*_l$ will not in general equal the initial one. The strategy just described treats all **p** in $P \cap G$ as equally good final in-gamut pictures, without regard to their distance from the original image. There may, however, be a modification to the model as implemented which would have as its goal finding the **p** in $P \cap G$ which is the "closest" to the original image, $\mathbf{p}_0$.

Figure 9 illustrates the steps in the implemented embodiment of device directed rendering method 90 which uses the mathematical model of the picture function to produce a semantically consistent color image with in-gamut pixel colors. First, in box 130, each scene spectrum in each of the symbolic pixel expressions 80 is assigned a variable representing the value for the weight on that spectrum, producing for each pixel expression an equation in the form of Equation (5) expressing the pixel color value as a function of the weights. The weights are also initialized from the input spectra. The input spectra are read from a vector n, and the values for the weights are stored in a vector **w**. The resulting scaled spectra are stored in vector **s**. If the input spectrum, $n_l(\lambda)$ is an illuminant, the value of the corresponding weight w_1 is initially set to one (1), and the spectrum $s_l \leftarrow n_l$. The values for input spectra which are illuminants must be positive, and may be greater than one (1). Otherwise, the input spectrum, $n_l(\lambda)$ is a reflectance. The value for a spectrum which is a reflectance must fall between zero and one, and so the value of the corresponding weight w_l is initially set to the largest input spectra value, and the spectrum $s_l \leftarrow n_l / w_l$. Thus, the largest value a weight may take on for a reflectance spectrum is one (1).

Other initialization functions may be performed in box 130 as well. For example, a number of user-specified thresholds are used to control subsequent processing steps, and these may be requested interactively from the user or otherwise entered into memory at this point.

In box 132, the symbolic pixel expressions 80 are then evaluated to produce a vector of evaluated pixels represented as tristimulus values. Evaluation step 132 is substantively similar to evaluation step 82 in FIG. 2, with modifications for handling the evaluated pixel expressions as a vector of spectral color information. The entire vector of values at this point is the initial picture, $\mathbf{p}_0$, also called the "ideal" image, as produced by the symbolic rendering system. All of the color and light intensity values in each symbolic pixel expression 80 which generate out-of-gamut pixel colors may be modified simultaneously, in the processing which follows. Typically, processing time and other implementation dependent decisions affect whether to modify all out-of-gamut colors at one time. In the illustrated embodiment, a selection of the "worst" pixel colors is made from all of the out-of-gamut pixels to reduce computational time. When these worst pixels are brought into gamut by adjusting the weights on the spectra, the picture is evaluated again, and a new set of "worst" pixels is selected for processing. The outer loop controls the selection of the worst out-of-gamut pixels, and an inner loop minimizes the picture function to bring the pixels in-gamut. However, all out-of-gamut pixels could be adjusted simultaneously, if computational time and system resources permit.

The number, *b*, of "worst" pixel colors selected is arbitrary, and is primarily influenced by performance constraints. The manner for selecting the pixels, in boxes 134 and 136, is as follows. Each evaluated pixel color is mapped to the device gamut to determine (a) whether the pixel is out-of-gamut; and (b) for each pixel that is out-of-gamut, (i) what the closest, in-gamut pixel color is, and (ii) what the distance is in the color space between the out-of-gamut color and the closest in-gamut color. The list of out-of-gamut pixels is sorted in descending order by distance, and the *b* number of pixels having the largest distance values are selected for processing. The symbolic pixel expressions 80 with weighted spectra which represent these worst pixels form the basis of the picture function, $\mathbf{p}_0$, which is the current ideal image.

In box 138, the inquiry is made whether all, or substantially all, of the pixels just evaluated are in the gamut of the designated output medium. This inquiry controls the outer loop of processing. When all pixels are in-gamut, processing is concluded, and the current set of evaluated pixels colors represent a color image which is semantically consistent and which has image pixels that are within the gamut of the output medium. Control then transfers to box 154, where the file of modified indexed color description data is produced. The current values for the weights contain the scale factors to be applied to the original indexed color descriptions (file 84 in FIG. 1) to produce the modified color description data (file 86 in FIG. 1). The process in box 154 applies each weight to its corresponding original color description according to the index in the symbolic pixel expression, and writes a data structure of modified color information data with corresponding indices.

The inquiry in box 138 may also permit the user to specify some user threshold to terminate processing. This threshold may specify for example, that each evaluated pixel must be within some small range of distance from the gamut (a "close enough" threshold), or that some percentage of pixels must be within the gamut to conclude processing.

When the inquiry in box 138 is not satisfied, the symbolic expressions of the picture function, $\mathbf{p}_0$, defined by the *b* selected pixels, are differentiated with respect to the weights to form the Jacobian matrix, in box 140,

and inner loop processing begins in box 142. The inner loop processing represents the specific processing steps needed for minimizing the goodness function, which in the illustrated embodiment is the squared Euclidian distance between two pictures in picture space. As noted above, the Jacobian matrix relates movements of the pixels to movements of the weights: $J_i\Delta w_i = \Delta p_i$. The expression for each pixel in this matrix contains symbolic expressions w_i for weights on the spectra.

In box 142, $\mathbf{p}_0$ is now denoted as $\mathbf{p}_i$, since minimizing the distance between two pictures may take several iterations of the inner loop, and with each iteration $\mathbf{p}_i$ changes as weights are adjusted. In box 142, $\mathbf{p}_i$, the set of the *b* worst pixels, is evaluated with respect to the current settings of the weights. These evaluated pixels are then mapped to the device gamut in box 144, using gamut projector function, *h*, which may be any conventional gamut mapping method. The mapping to the gamut of picture $\mathbf{p}_i$ produces a target picture $\mathbf{p}^*$, a list of in-gamut pixels. Then, also in box 142, the difference $\Delta\mathbf{p}$ between each pixel color in the current picture $\mathbf{p}_i$ and the target picture $\mathbf{p}^*$ is computed.

In boxes 146 and 148, the specific Jacobian matrix for picture $\mathbf{p}_i$ is constructed and its pseudo-inverse computed, using any standard technique, to find the direction in which to move the weights to bring the current picture closer to the target picture in picture space. In box 150, a step size is selected for the weights, according to how nonlinear picture function $f(w_i)$ is. In the illustrated embodiment, the step size takes on a user-specified value *m* between 0 and 1. If the largest absolute value in the vector of weight changes computed from the pseudo-inverse of the Jacobian is greater than *m*, the step size is set to *m;* otherwise, the step size is set to one (1). The new weights are found from $w_{i+1} \leftarrow w_i + k\Delta w_i$.

In box 152, an inquiry is made as to whether the inner loop processing is completed. In essence the inquiry is whether the current picture of the b worst pixels from the outer loop satisfies the goodness function. The inquiry is made here because the most recent set of computed changes for the weights provides information as to how the current picture is "converging" on the target picture. The specific inquiry in box 152, then, includes two tests. The first is whether the absolute value of the largest distance difference between the current picture and the target picture is within a user-specified distance. The second is whether the absolute value of the largest change in the weights computed from the Jacobian pseudo-inverse is smaller than a user-specified quantity, that is, too minimal to try another iteration of weight changes. If either test is true, processing of the inner loop is terminated, and processing continues in box 132. If either test is not true, however, the distance function may be minimized further, and processing is transferred to the top of the inner loop at box 142.

The method of the present invention may be used for operating a processor-controlled machine, such as a general purpose digital computer or a machine having a digital computer as a component part. In addition, the present invention may be a machine which includes a processor for executing instructions which accomplish substantially similar results as the method of the present invention. Figure 10 illustrate a machine configuration for which the present method and machine inventions are suitable. Figure 10 is a simplified functional block diagram illustrating the components of a processor-controlled machine 200 (hereinafter, "system 200"). System 200 may be a standalone system, such as a microcomputer-based graphics workstation, which is suitable for performing the scene modeling and creation of the scene description, the rendering of the image with a symbolic shaded rendering system, the spectral change calculations method 90 of the present invention, and display of the in-gamut final color image on output device 49. The components of system 200 include a processor 204 and at least one memory unit 202. Memory unit 202 includes ROM and RAM in which are stored the program instructions for the scene modeling application, the rendering system, spectral change calculator 90, and the symbolic pixel expression evaluator. Memory 202 also stores data that may be needed during execution of the program instructions, including the scene description 22, indexed color description data 84, the symbolic pixel expressions 80, and device gamut data 44.

In system 200, processor 204 is connected for access to and in communication with a respective memory unit, and processor 204 controls the execution of program instructions and the retrieval of data from the memory. Processor 204 may be any appropriate processor and, in use, it controls the transfer of pixel information signals representing pixel image data from memory to output circuitry which includes output unit 49.

Input unit 206 may include any suitable device and associated input circuitry for interacting with a scene modeling application, a rendering system 25, and spectral change calculator 90. Suitable devices include but are not limited to pointing and cursor control devices for two- and three-dimensional displays, such as a mouse or light pen, alphanumeric input devices such as a keyboard, and touch screen displays.

The output units of system 200 may be any appropriately connected color device suitable for displaying computer generated color image data, such as a cathode ray tube (CRT) raster scan color monitor or a color liquid crystal display. Other devices suitable as output units in place of display 49 include color reproduction devices, such as an electronic or digital printer, xerographic marking engine, platemaking device, or other suitable color rendering device. In addition, the output unit may be a data communications device for connecting to a communications line, as shown in FIGS. 11 and 12, whereby data created according to the method of the

present invention may be transmitted to other suitably configured systems for further processing or for display or reproduction.

In FIG. 11, in an alternative embodiment of the present invention, another machine configuration having two, similarly configured, processor-controlled machines is illustrated. System 200 is connected to system 210 through communications link 209, which may be any conventional network communications connection between the two machines. System 200, which may be a graphics workstation, is operated to execute rendering system instructions 25 to generate symbolic pixel expression file 80 and indexed color description data 84, which together represent the data needed for a rendered color image, and which may be stored in memory 202. Processor 204 controls the communication of symbolic pixel expression file 80 and indexed color description data 84 to receiving system 210 through output unit 208 configured as a communications connection. The receiving system 210, which may be a networked, microcomputer or workstation, receives symbolic pixel expression file 80 and indexed color description data 84 from system 200 through communications link 209, and executes spectral change calculation instructions 90 and symbolic pixel expression evaluator instructions 82 to produce the in-gamut image pixel color data 46 needed for displaying the in-gamut rendered color image on output display 49 of system 210.

A second alternative embodiment is shown in FIG. 12: there is illustrated still another machine configuration having three processor-controlled machines connected through communications links 209 and 219. This implementation is described in detail in Ref. 1 with reference to FIG. 10 thereof.

Other machine implementations of the functional steps of the method of the present invention are also possible. For example, in FIG. 12, system 210 could also generate the in-gamut image pixel color data 46 using symbolic pixel expression evaluator 82, thereby creating the data which represents the final color image having colors which are in the gamut of designated output medium 49 of system 220. System 220 could then receive the in-gamut image pixel color data 46 through communications link 219, for display on output medium 49 without further processing. The dotted line 88 of FIG. 1 represents the combination of spectral change calculator process 90 with symbolic pixel expression evaluator process 82 implemented on a single machine.

The method of the present invention was implemented on a Sun Microsystems SPARCstation Model 2 with a 24 bit color display, running the Unix BSD 4.2 operating system. The renderer used in the illustrated embodiment was implemented as a ray tracing rendering method from a simple public domain ray tracer, available at the time of implementation via anonymous ftp from "princeton.edu" under the name of "*MTV*".

The gamut projector function *h* may be implemented as any suitable gamut mapping process known in the art. In the illustrated embodiment, a very simple gamut mapping process is used which projects each out-of-gamut pixel in the current ideal image, picture $\mathbf{p}_0$, onto the position in the gamut in RGB color space closest to the out-of-gamut pixel position. Table 2 of Ref. 1 contains the program code, in *Mathematica*, to implement this simple gamut projector function to find the signed distance from an ideal image pixel color to the closest point in the RGB color space:

FIGS. 12A and 12B of Ref. 1 contain an example of the program code, in *Mathematica*, designated as reference numeral 160 in both figures, to implement the steps shown in FIG. 9.

The present invention furthermore encompasses variations of the above described embodiments which will be apparent to persons skilled in the art and, for example, as described on pp. 55-57 of Ref. 1.

Claims

1. A method of rendering a colour image from symbolic image data, comprising:
   performing spectral change calculations with symbolic color image data, indexed color description data indexed to the symbolic color image data, and device gamut color data representing a gamut of device colors of a color reproduction device to produce modified color description data; the modified color description data, when used to evaluate the symbolic color image data, generating a color image composed of a plurality of in-gamut colors; each in-gamut color being one of the device colors in the gamut of the color reproduction device.

2. The method of claim 1 wherein performing spectral change calculations includes the steps of:
   (a) determining color modification data to be used to modify the indexed color description data;
   (b) evaluating the symbolic color image data with the indexed color description data and the color modification data to generate a color image composed of modified colors;
   (c) generating a target color image from the color image using the device gamut color data; each of a plurality of target colors composing the target color image being one of the device colors in the gamut of the color reproduction device and corresponding to one of the modified colors of the color image;

(d) determining whether the color image satisfies an image metric measuring a valid color image in terms of a relationship between the color image and the target color image;
(e) if the color image does not satisfy the image metric, repeating steps (a), (b), (c), and (d) until the color image satisfies the image metric; and
(f) modifying the indexed color description data with the color modification data to produce the modified color description data.

3. The method of claim 2 wherein the image metric measures the valid color image according to a distance in a color space between one of the modified colors in the color image and the corresponding target color in the target color image.

4. A method of rendering a colour image from symbolic image data, comprising:
(a) assigning change variables to symbolic color image data items;
(b) evaluating the symbolic color image data items with indexed color description data items to generate a current color image composed of current colors;
(c) generating, from the current colors of the current color image, a target color image using device gamut color data;
(d) calculating difference data between the current colors and the target colors;
(e) determining incremental change quantities for the values of the change variables using the difference data;
(f) determining from the difference data and from the incremental change quantities whether the current color image satisfies image metric data; the image metric data including relationship data for measuring a valid color image in terms of a relationship between the current color image and the target color image, and change variable data for measuring a minimum acceptable quantity for the incremental change quantities;
(g) if the current color image does not satisfy the image metric data, updating the current values of the change variables with the incremental change quantities, and repeating steps (b), (c), (d), (e), (f) and (g); and
(h) applying the current values of the change variables to the indexed color description data to produce modified color description data.

5. The method of claim 4 wherein the relationship data of the image metric data measures the current color image according to a distance in a color space between one of the current colors in the current color image and the corresponding target color in the target color image.

6. A method of operating a machine for rendering a colour image from symbolic image data, the machine including:

a memory for storing data; and

a processor connected for accessing and storing data in the memory;

the data stored in the memory including

indexed color description data items; each indexed color description data item defining an original color of one of a plurality of object primitives in a scene description;

symbolic color image data items having symbolic spectral components indexing the indexed color description data items to the symbolic color image data items; each symbolic color image data item defining one of a plurality of image pixel color data items composing a color image rendered from the scene description;

device gamut color data items representing for a color reproduction device a gamut of device colors capable of reproduction by the device; and

image metric data representing a desired relationship between the plurality of image pixel color data items composing the color image and a plurality of target image pixel color data items composing a target color image;

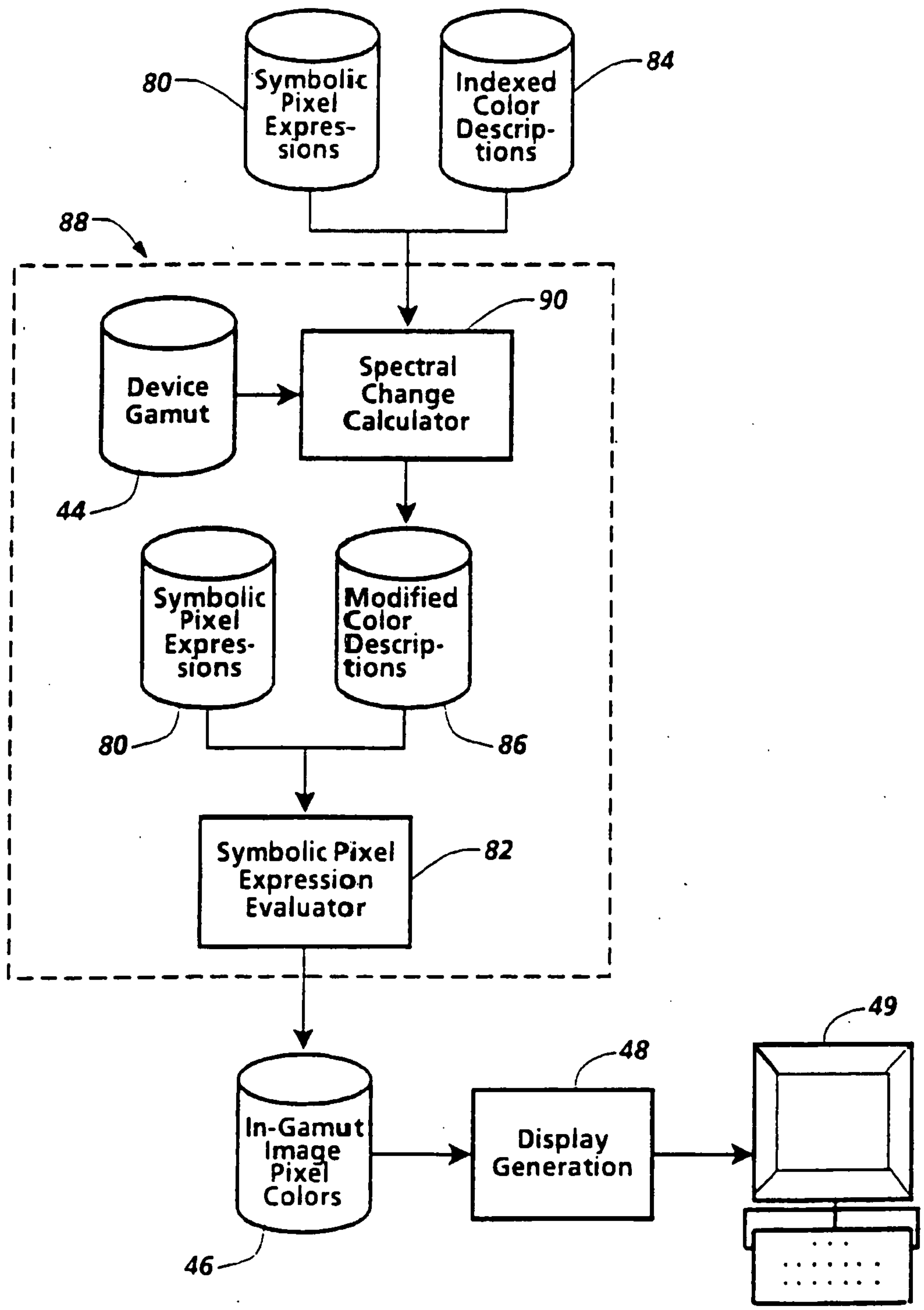
the method comprising the following steps carried out by the processor:
(a) assigning change variables to the symbolic spectral components in the symbolic color image data items stored in the memory of the machine;
(b) determining a new value for at least one change variable to produce modified symbolic spectral components;
(c) evaluating each modified symbolic spectral component of each symbolic color image data item with the indexed color description data items to produce the image pixel color data items composing the

color image;
(d) generating the plurality of target image pixel color data items composing the target color image from the image pixel color data items composing the color image using the device gamut color data items; each target image pixel color data item representing one of the device colors capable of reproduction by the device;
(e) determining if the color image satisfies the relationship represented by the image metric data;
(f) if the color image does not satisfy the image metric data, repeating steps (b), (c), (d), and (e) until the color image satisfies the image metric data; and
(g) applying the new value of each change variable to the indexed color description data item indexed to the symbolic spectral component to generate a plurality of modified indexed color description data items.

7. A machine for rendering a colour image from symbolic image data, comprising:
input circuitry for obtaining symbolic color image data items and indexed color description data items; each indexed color description data item defining an original color of one of a plurality of object primitives in a scene description; each symbolic color image data item defining one of a plurality of image pixel color data items composing a color image rendered from the scene description; the symbolic color image data items having symbolic spectral components indexing the indexed color description data items to the symbolic color image data items;
memory for storing data;
output circuitry for connecting the machine to an output medium and for transferring selected data from the memory to the output medium; and
a processor connected for accessing the input circuitry to receive the symbolic color image data items and the indexed color description data items and to store the symbolic color image data items and the indexed color description data items in the memory; the processor further being connected for accessing the output circuitry to transfer the selected data from the memory to the output circuitry;
the processor further being connected for accessing data stored in the memory; the data stored in the memory including:
device gamut color data items representing a gamut of device colors capable of reproduction by a color reproduction device; and
instruction data indicating instructions the processor executes;
the processor, in executing the instructions, performs spectral change calculations with the symbolic color image data items, the indexed color description data items, and the device gamut color data items to produce modified color description data items capable of producing, together with the symbolic color image data items, the plurality of image pixel color data items composing the color image; each image pixel color data item representing one of the device colors in the gamut of the color reproduction device; the processor further, in executing the instructions, stores the modified color description data items in the memory.

8. The machine of claim 8 wherein the processor further, in executing the instructions, (1) selects the modified color description data items and the symbolic color image data items in the memory and transfers the selected data items from the memory to the output circuitry; the output circuitry transferring the modified color description data items and the symbolic color image data items to the connected output medium or (2) evaluates the symbolic color image data items with the modified color description data items to generate the image pixel color data items composing the color image; and wherein the processor further, in executing the instructions, transfers the plurality of image pixel color data items to the output circuitry for transferring to the output medium.

9. The machine of claim 8 or 9 wherein the output medium is (1) the color reproduction device having the gamut of device colors represented by the device gamut color data items stored in the memory of the machine or (2) a data communications circuit.



80
Symbolic Pixel Expres-sions
Indexed Color Descrip-tions
84
88
90
Device Gamut
Spectral Change Calculator
44
Symbolic Pixel Expres-sions
Modified Color Descrip-tions
80
86
Symbolic Pixel Expression Evaluator
82
49
48
In-Gamut Image Pixel Colors
Display Generation
46

FIG. 1

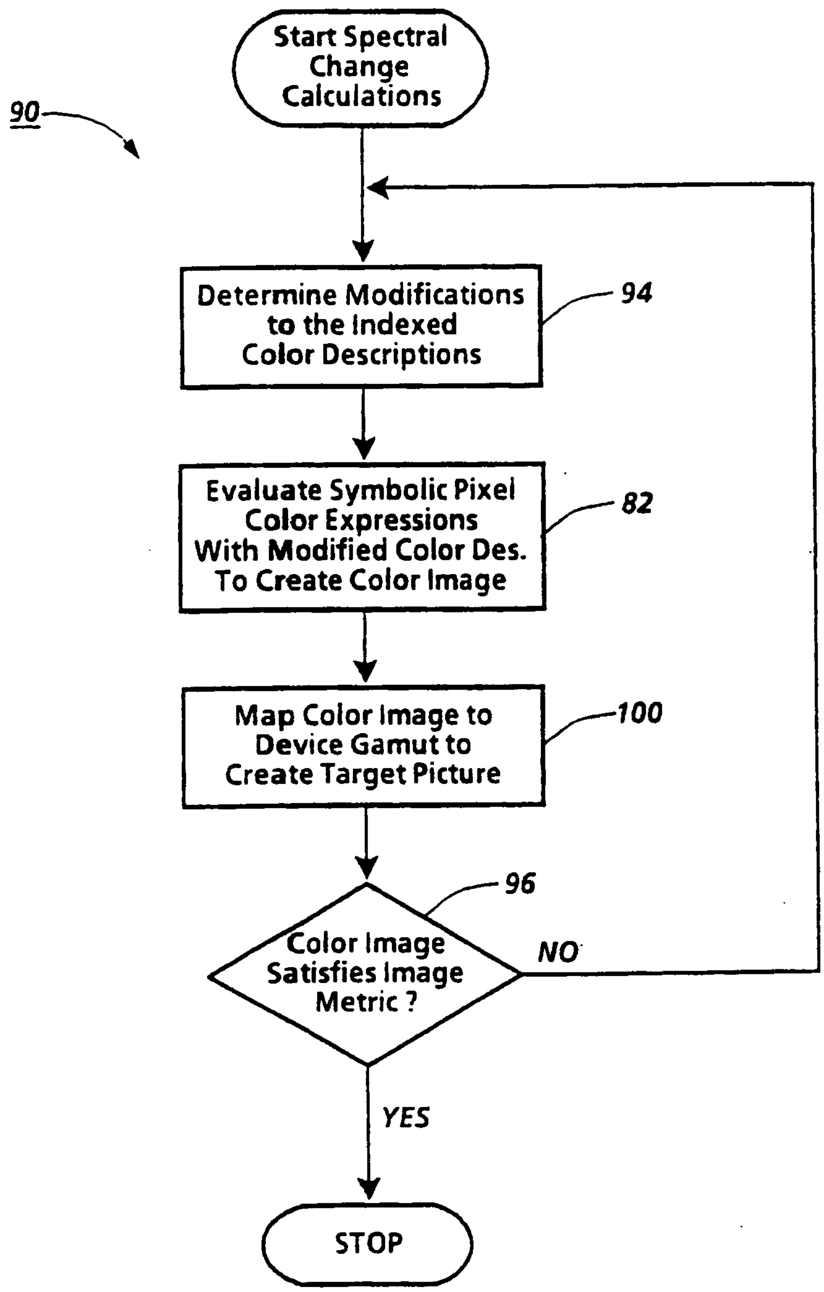

Start Spectral Change Calculations
90
Determine Modifications to the Indexed Color Descriptions
94
Evaluate Symbolic Pixel Color Expressions With Modified Color Des. To Create Color Image
82
Map Color Image to Device Gamut to Create Target Picture
100
Color Image Satisfies Image Metric ?
96
NO
YES
STOP

Fig. 2

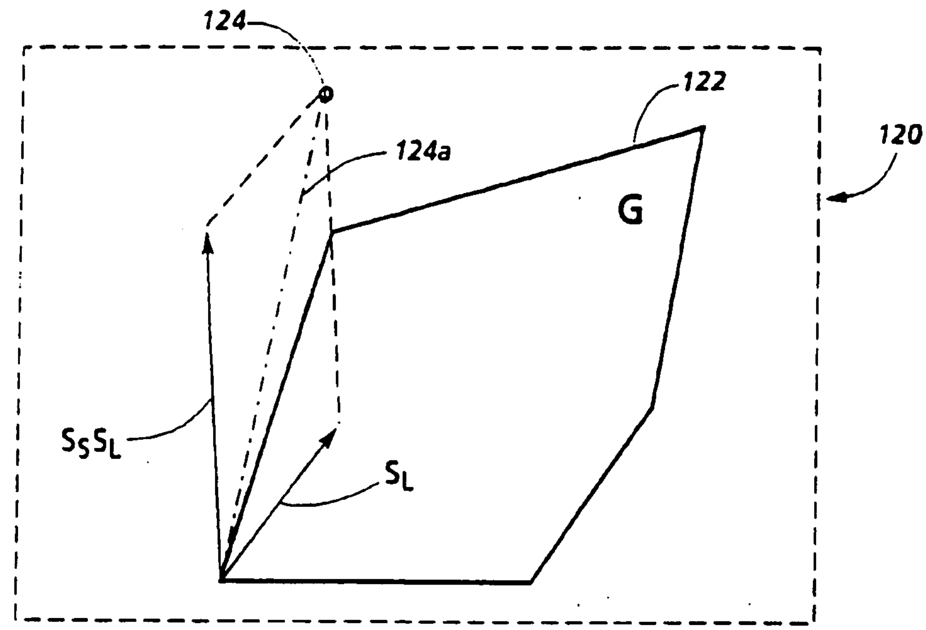

124
122
120
124a
G
$S_S S_L$
S_L

Fig. 3

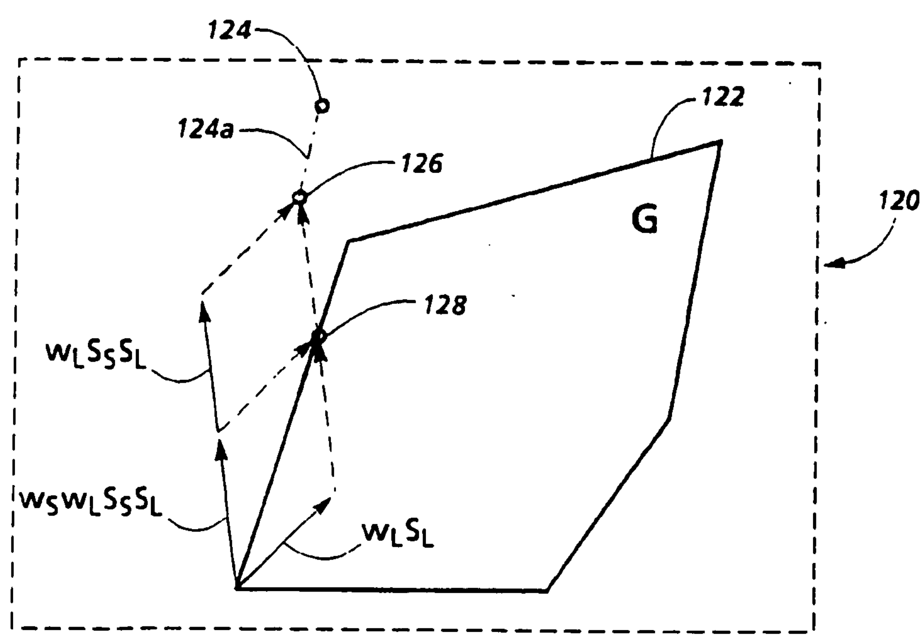

124
122
124a
126
120
G
128
$w_L S_S S_L$
$w_S w_L S_S S_L$
$w_L S_L$

FIG. 4

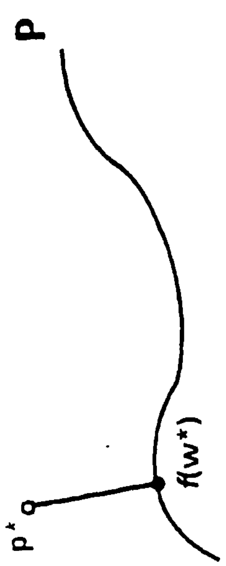


FIG. 5

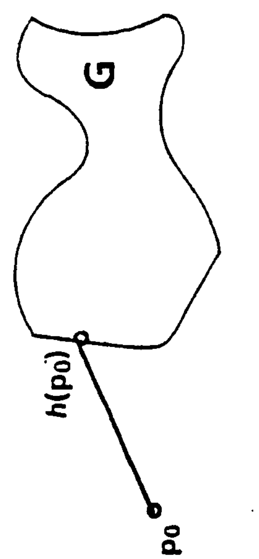


FIG. 6

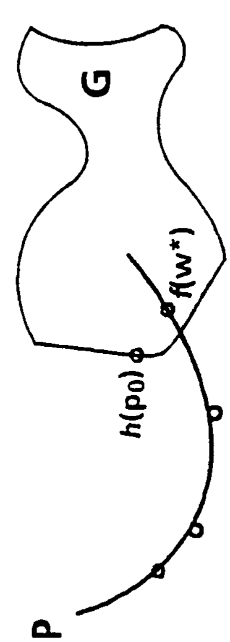


FIG. 7

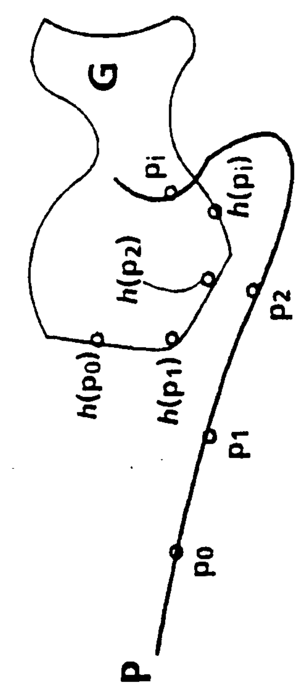


Fig. 8

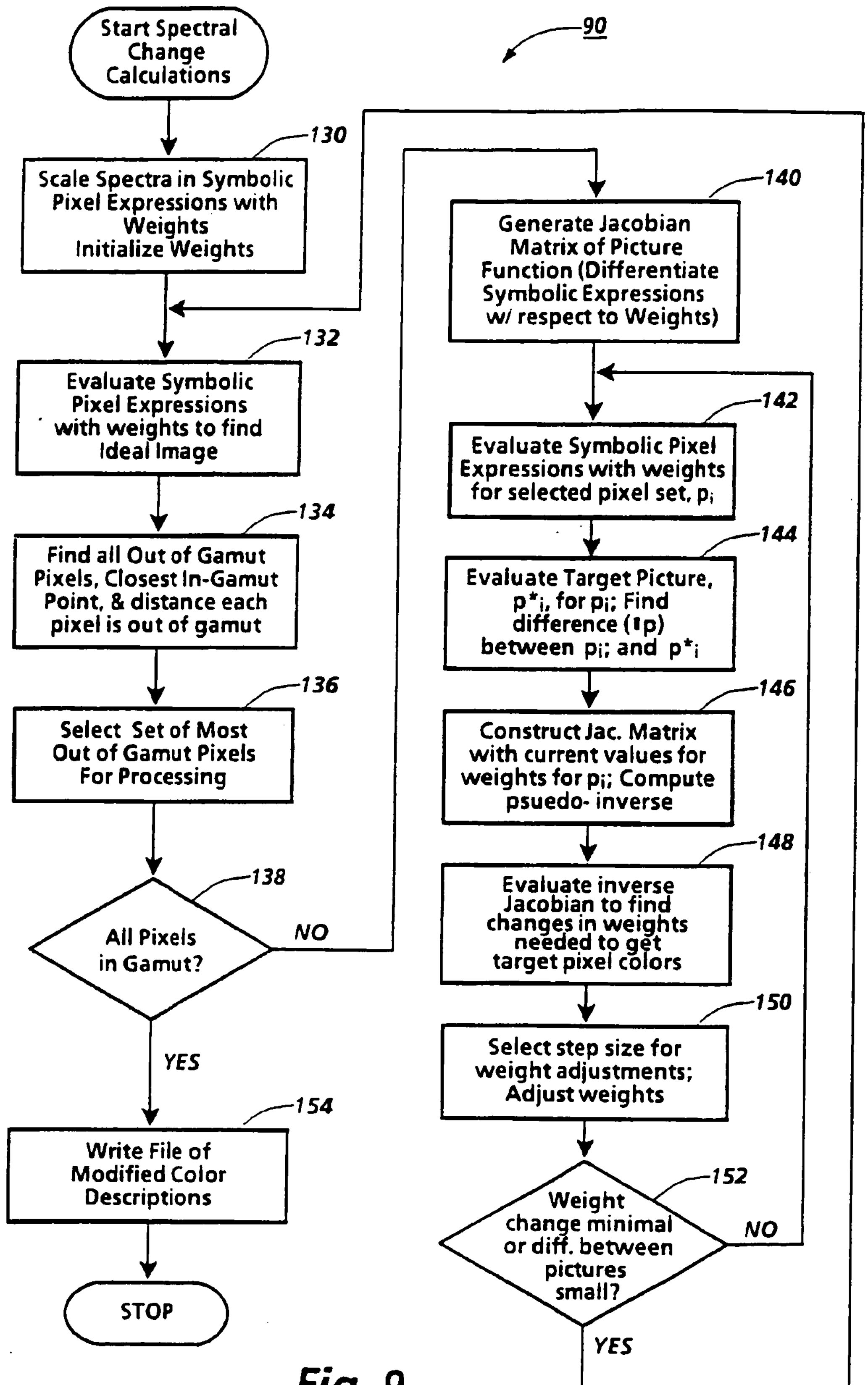

90
Start Spectral Change Calculations
130
Scale Spectra in Symbolic Pixel Expressions with Weights
Initialize Weights
132
Evaluate Symbolic Pixel Expressions with weights to find Ideal Image
134
Find all Out of Gamut Pixels, Closest In-Gamut Point, & distance each pixel is out of gamut
136
Select Set of Most Out of Gamut Pixels For Processing
138
All Pixels in Gamut?
NO
YES
154
Write File of Modified Color Descriptions
STOP
140
Generate Jacobian Matrix of Picture Function (Differentiate Symbolic Expressions w/ respect to Weights)
142
Evaluate Symbolic Pixel Expressions with weights for selected pixel set, p_i
144
Evaluate Target Picture, p^*_i, for p_i; Find difference (Ip) between p_i; and p^*_i
146
Construct Jac. Matrix with current values for weights for p_i; Compute psuedo- inverse
148
Evaluate inverse Jacobian to find changes in weights needed to get target pixel colors
150
Select step size for weight adjustments; Adjust weights
152
Weight change minimal or diff. between pictures small?
NO
YES

Fig. 9

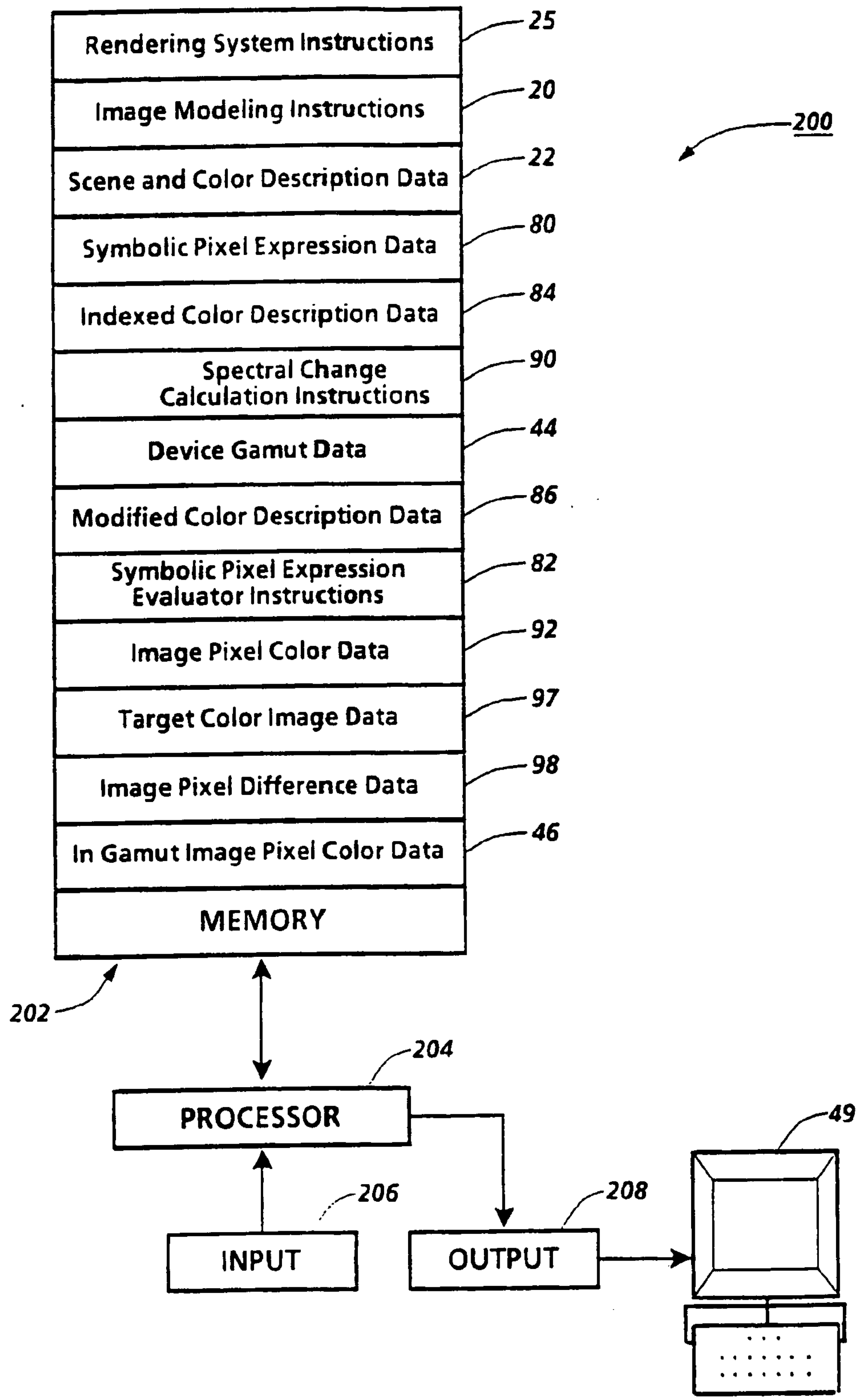
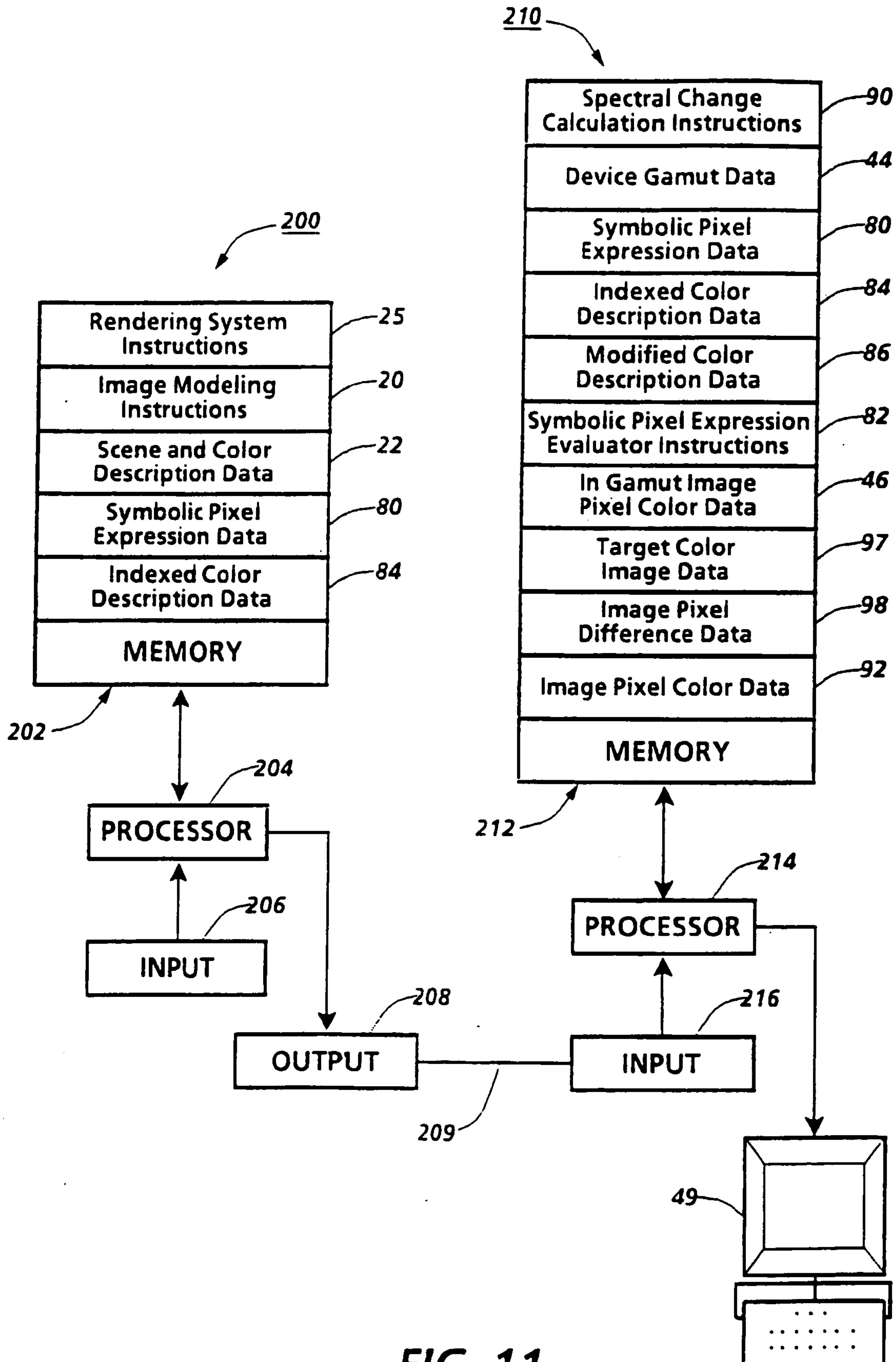

Rendering System Instructions
25
Image Modeling Instructions
20
200
Scene and Color Description Data
22
Symbolic Pixel Expression Data
80
Indexed Color Description Data
84
Spectral Change Calculation Instructions
90
Device Gamut Data
44
Modified Color Description Data
86
Symbolic Pixel Expression Evaluator Instructions
82
Image Pixel Color Data
92
Target Color Image Data
97
Image Pixel Difference Data
98
In Gamut Image Pixel Color Data
46
MEMORY
202
204
PROCESSOR
49
206
208
INPUT
OUTPUT

Fig.10



210
Spectral Change Calculation Instructions
90
Device Gamut Data
44
Symbolic Pixel Expression Data
80
Indexed Color Description Data
84
Modified Color Description Data
86
Symbolic Pixel Expression Evaluator Instructions
82
In Gamut Image Pixel Color Data
46
Target Color Image Data
97
Image Pixel Difference Data
98
Image Pixel Color Data
92
MEMORY
212
200
Rendering System Instructions
25
Image Modeling Instructions
20
Scene and Color Description Data
22
Symbolic Pixel Expression Data
80
Indexed Color Description Data
84
MEMORY
202
PROCESSOR
204
INPUT
206
OUTPUT
208
209
PROCESSOR
214
INPUT
216
49

FIG. 11

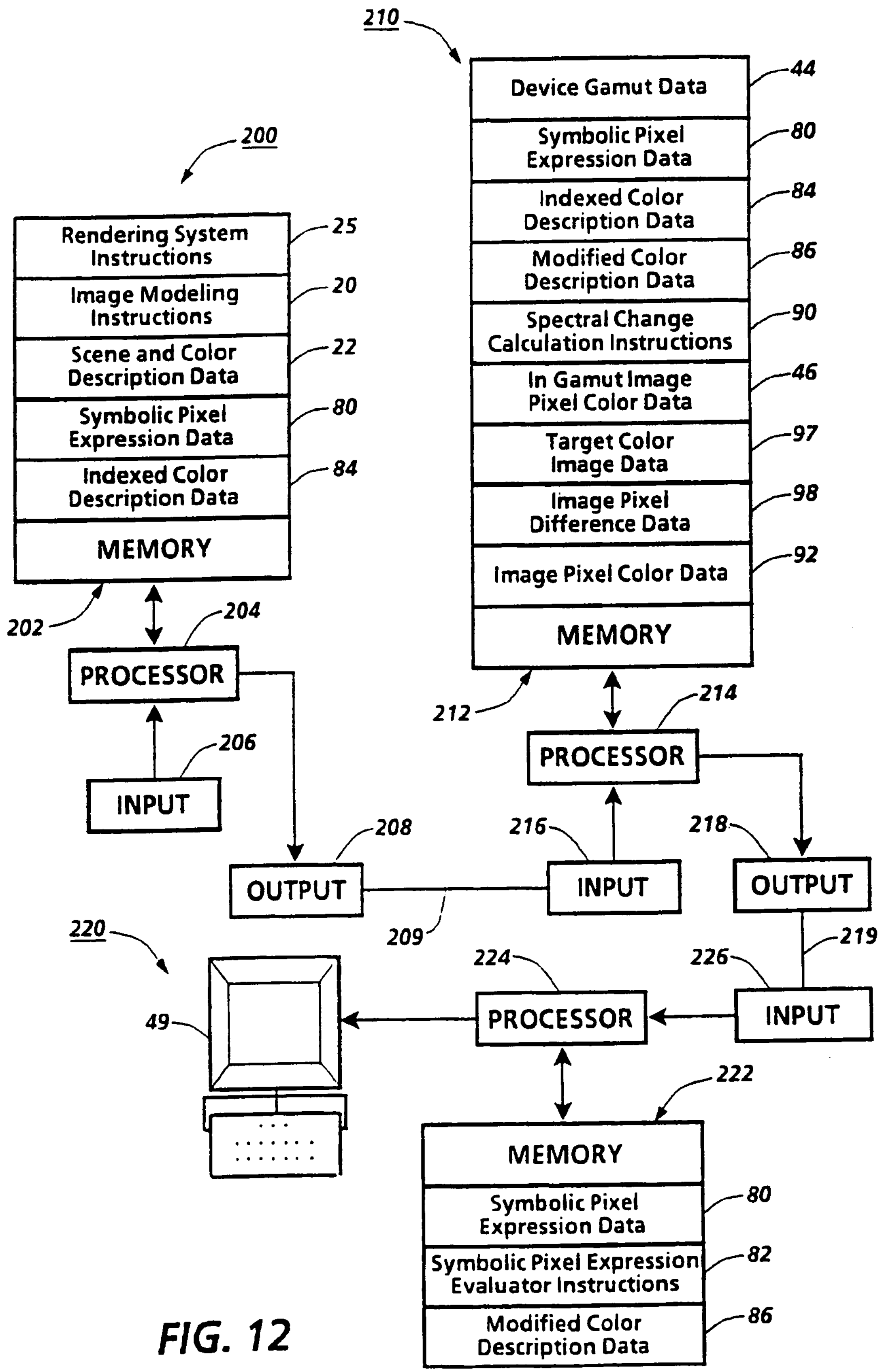

210
Device Gamut Data
44
Symbolic Pixel Expression Data
80
Indexed Color Description Data
84
Modified Color Description Data
86
Spectral Change Calculation Instructions
90
In Gamut Image Pixel Color Data
46
Target Color Image Data
97
Image Pixel Difference Data
98
Image Pixel Color Data
92
MEMORY
212
PROCESSOR
214
200
Rendering System Instructions
25
Image Modeling Instructions
20
Scene and Color Description Data
22
Symbolic Pixel Expression Data
80
Indexed Color Description Data
84
MEMORY
202
PROCESSOR
204
INPUT
206
OUTPUT
208
209
INPUT
216
OUTPUT
218
219
INPUT
226
PROCESSOR
224
220
49
222
MEMORY
Symbolic Pixel Expression Data
80
Symbolic Pixel Expression Evaluator Instructions
82
Modified Color Description Data
86

FIG. 12

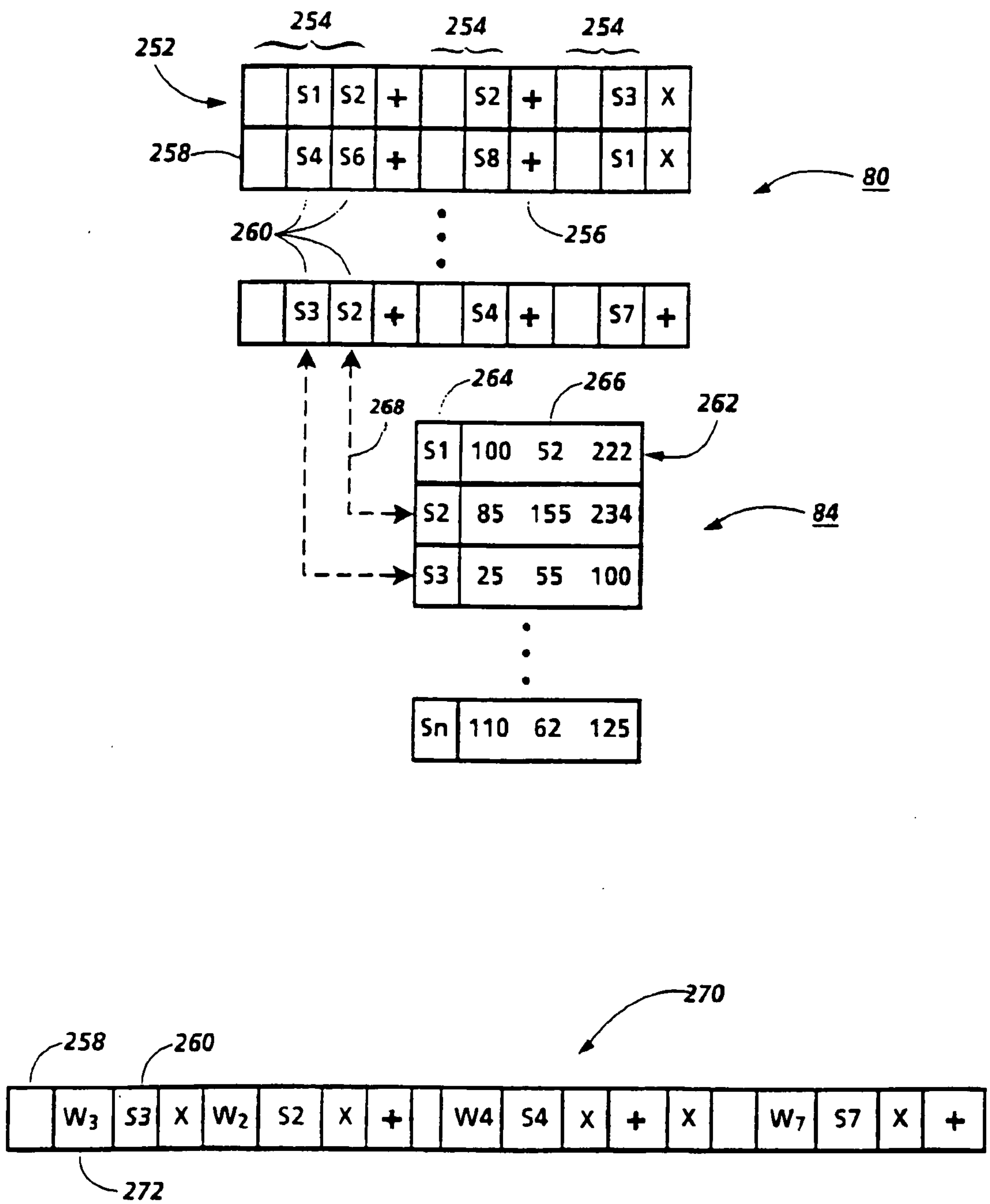

254
254
254
252
S1
S2
+
S2
+
S3
X
258
S4
S6
+
S8
+
S1
X
80
260
256
S3
S2
+
S4
+
S7
+
264
266
262
268
S1
100 52 222
S2
85 155 234
84
S3
25 55 100
Sn
110 62 125
270
258
260
W3
S3
X
W2
S2
X
+
W4
S4
X
+
X
W7
S7
X
+
272

Fig.13

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 93 30 8229

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
X	EP-A-0 475 554 (SCITEX CORP.) 18 March 1992 * page 25, line 15 - line 43; claim 1; figures 4-6,10 * ---	6-8	G06F15/72
A	ACM TRANSACTION ON GRAPHICS vol. 7, no. 4 , October 1988 , USA pages 249 - 292 STONE ET AL. 'color gamut mapping and the printing of digital color images' * page 257, line 10 - page 265, line 7 * * page 272, line 25 - page 275, line 23 * * page 278, line 18 - page 280, line 28 * ---	1-10	
P,A	US-A-5 243 414 (DALRYMPLE ET AL.) ---		
A	PROCEESINGS. GRAPHICS INTERFACE '91 3 June 1991 , CANADA pages 32 - 39 STONE ET AL. 'gamut mapping computer generated imagery' -----		

TECHNICAL FIELDS SEARCHED (Int.Cl.5)

G06F
H04N

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	14 February 1994	Perez Molina, E

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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